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Contributions of individual countries' emissions to climate change and their uncertainty

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Abstract We have compiled historical greenhouse gas emissions and their uncertainties on country and sector level and assessed their contribution to cumulative emissions and to global average temperature increase in the past and for a the future emission scenario. We find that uncertainty in historical contribution estimates differs between countries due to different shares of greenhouse gases and time development of emissions. Although historical emissions in the distant past are very uncertain, their influence on countries' or sectors' contributions to temperature increase is relatively small in most cases, because these results are dominated by recent (high) emissions. For relative contributions to cumulative emissions and temperature

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rise, the uncertainty introduced by unknown historical emissions is larger than the uncertainty introduced by the use of different climate models. The choice of different parameters in the calculation of relative contributions is most relevant for countries that are different from the world average in greenhouse gas mix and timing of emissions. The choice of the indicator (cumulative GWP weighted emissions or temperature increase) is very important for a few countries (altering contributions up to a factor of 2) and could be considered small for most countries (in the order of 10%). The choice of the year, from which to start accounting for emissions (e.g. 1750 or 1990), is important for many countries, up to a factor of 2.2 and on average of around 1.3. Including or excluding land-use change and forestry or non-CO_2 gases changes relative contributions dramatically for a third of the countries (by a factor of 5 to a factor of 90). Industrialised countries started to increase CO_2 emissions from energy use much earlier. Developing countries' emissions from land-use change and forestry as well as of CH_4 and N_2O were substantial before their emissions from energy use.

1 Introduction

As part of the negotiations of the Kyoto Protocol, the delegation of Brazil presented an approach for allocating greenhouse gas emission reductions among OECD countries and economies in transition (the so-called Annex I Parties) based on the effect of their cumulative historical emissions of greenhouse gases included in the Kyoto Protocol,[1] from 1840 onwards, on the global-average surface temperature (UNFCCC 1997). While the "Brazilian Proposal" was initially developed to further discussions on differentiation of commitments among Annex I countries, it can also be used as a framework for allocating emission reduction burdens across all countries. The proposal's central idea was that there exists a functional link between GHG emissions and global temperature increase, or other indicators along the cause–effect chain of climate change, such that the indicator can be calculated from the emissions using a simple model or set of models. The indicator acts as a surrogate for climate impacts, which are more difficult to reliably calculate using simple global average models. The methodology also assumes that it is possible to apportion the contributions to the change in the indicator between a number of sources and emitters (e.g. nations, regions).

Although the Brazilian Proposal was not adopted during the Kyoto negotiations, it did receive support and the Third Conference of the Parties (COP-3) requested the Subsidiary Body on Scientific and Technical Advice (SBSTA) to further study the methodological and scientific aspects of the proposal. This led to continued debate and analysis (e.g. Pinguelli Rosa and Ribeiro 1997, 2001; Enting 1998; Filho and Miguez 1998; den Elzen et al. 1999; den Elzen and Schaeffer 2002; Höhne 2002; Rosa et al. 2004) and a number of expert meetings organised by the UNFCCC secretariat. The objective of these meetings was to review the scientific and methodological

[1] Six GHGs or groups of GHGs are covered under the Kyoto Protocol, i.e. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

aspects of the proposal and to co-ordinate an intercomparison of attribution results using a set of simple climate models in an exercise called the Assessment of Contributions to Climate Change (ACCC). The conclusions of this analysis are described in UNFCCC (2002), and some institutes have reported their analysis in more detail (e.g. den Elzen et al. 2002, 2005b; Andronova and Schlesinger 2004; Höhne and Blok 2005; Trudinger and Enting 2005).

A follow up exercise has now been carried out by an ad-hoc group for the modelling and assessment of contributions of climate change (MATCH) (Höhne and Ullrich 2003) to improve the robustness of calculations and more rigorously assess the uncertainties and methodological choices.

The first paper from the MATCH group (den Elzen et al. 2005a) addressed these central questions: how robustly can simple climate models (SCMs) be used to attribute anthropogenic climate change to sources of GHGs (e.g. regional sources) and what effect do a range of scientific choices (related to scientific uncertainties) and policy-related choices[2] that are part of the negotiation process, have on these attribution calculations? The approach was to illustrate the effects of making reasonable alternative parameter choices and it was left to future work to rigorously sample the entire parameter space and to provide a review of the underpinning science on which this attribution method is based.

A second effort from the MATCH group (Prather et al. 2009) addressed the full chain of uncertainty from emission estimates to increase in temperature for a group of countries. They estimate uncertainty in contribution of the Annex I countries for the period 1990–2002 to be ±17% and concluded that this relative uncertainty would increase, if the period of emissions is extended backward to 1900 or the evaluation time is extended to 2100.

One modelling group participating in MATCH has provided details on land-use change and forestry emissions (LUCF) and country level contribution calculations (de Campos 2007) or sectoral level calculations (Muylaert de Araujo et al. 2007).

A third paper (Ito et al. 2008) reconciles different estimates of emissions from forestry, as this was identified as a major source of uncertainty. They developed a consolidated estimate of the terrestrial carbon fluxes for the USA and Brazil as case studies. Because there are different sources of errors at the country level, there is no easy reconciliation of different estimates of carbon fluxes at the global level. Clearly, further work is required to develop data sets for historical land cover change areas and models of biogeochemical changes for an accurate representation of carbon uptake or emissions due to land-use change.

The purpose of this current paper is to present an update of the first joint MATCH paper (den Elzen et al. 2005a) and include new elements not covered by previous papers:

- Country level calculations of contributions to climate change
- Contributions split by sectors (energy and industry, agriculture and waste, land use change and forestry)
- Evaluation of the effect of the uncertainty in historic emission estimates.

[2]The term ‘policy choice’ or ‘policy-related choice’ refers to variables in the calculation, the values of which can not be based on objective (‘scientific’) arguments alone den Elzen et al. (2002).

Our approach is to provide finer scale (i.e. per country and sector) results for the most important scientific and political choices identified in den Elzen et al. (2005a). We omit the choices that were shown to not make a large difference in the previous analysis. The approach is pragmatic and result-oriented as opposed to all encompassing. Our new database on emissions and contribution to climate change is available electronically.[3]

The recent discussions at UNFCCC meetings in the preparation of a new international agreement on climate change have shown the interest for such data on historical emissions and contributions to climate change. “Historical responsibility” is one of the key factors to decide which countries need to take action in reducing emissions or in contributing to funds to adapt to climate change. The Ad Hoc Working Group on Long-term Cooperative Action (AWG-LCA) under the UNFCCC is charged to negotiate a new agreement and has held a technical briefing on historical responsibility on 4 June 2009.[4]

We make a clear distinction between “contribution” to temperature increase and “historical responsibility”. This paper covers only “contributions”, which is the cause effect relation between emissions of a country or sector and climate change. This does not automatically imply who is morally responsible for the effects. Such judgements are not the subject of this paper, but are included elsewhere (see e.g. Müller et al. 2009).

For clarity we note that the term “attribution” is used in this work to describe the contribution of a given source of emissions (country, country group or greenhouse agent) to a specified indicator of anthropogenic climate change. In some sections of the climate change literature (for instance Stott 2003; Zwiers and Zhang 2003) the term attribution is instead taken to refer to the fraction of observed global climate change that can be attributed to either natural factors, increasing global GHG concentrations or changes in aerosol particles, rather than to assess the contribution of a group of nations.

2 Methodologies

Five modelling groups took part in providing simulations for the current work, see Table 2. Each modelling group used the same historical emission data set (see Section 2.1) and a fixed set of alternative parameters (see Section 2.2), but their own simple climate models (Section 2.3). This enabled us to compare the effect on the contribution calculations caused by the uncertainty of emissions with the effect cause by the uncertainty due to the use of different simple models.

2.1 Emission dataset and emission uncertainties

A new emission datasets has been compiled with results for 192 countries or regions for three sectors: energy and industry (CO_2, CH_4, N_2O), agriculture/waste

[3] http://www.match-info.net

[4] http://unfccc.int/meetings/ad_hoc_working_groups/lca/items/4891.php

Table 1 Emission datasets and sectoral uncertainty factors (roughly one sigma, i.e. 16th and 84th percentile)

	Edgar/Hyde	CDIAC	USEPA	IEA	UNFCCC	IMAGE SRES scenarios
	5	4	3	2	1	6
	1890–1990	1750–2003	1990–2000	1970–2004	1990–2004	1970–2100
	Region	Country	Country	Country	Country	Region
Energy and industry CO_2	1.3	1.15		1.1	1.05	1.15
Energy and industry CH_4/N_2O	2		1.75		1.5	2
Agriculture/waste CH_4	2		1.5		1.35	2
Agriculture/waste N_2O	5		4		3	5
Land use change and forestry CO_2	Two datasets: Houghton (2003) and de Campos and Muylaert Rosa (2005) Upper limit: max of both Best estimate: average of both Lower limit: min of both					

Uncertainty factors imply a log normal distribution

(non-CO_2) and land use change and forestry (CO_2) from 1750 to 2100. Hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride were not included as historical emission estimates were not available on a gas-by-gas level. Total cumulative GWP-weighted historical emissions of these omitted gases (as collected in Höhne and Blok 2005) amount to about 0.5% of total cumulative historical emissions of CO_2, CH_4 and N_2O collected here, using IPCC 1995 GWPs with a 100-year time horizon. The effect on the global average temperature is also small (den Elzen et al. 2005a).

The emissions database was compiled by first collecting historical and future emission estimates by country or region, by gas and by sector from the following sources and ordered them in the following hierarchy (see also Table 1) based on expert judgement. The datasets vary in their completeness and sectoral split:

1. National submissions to the UNFCCC as collected by the UNFCCC secretariat and published in the GHG emission database available at their web site. For Annex I countries the available year from 1990 to 2004 were used. Most non-Annex I countries report only or until 1994 (UNFCCC 2005)
2. CO_2 emissions from fuel combustion as published by the International Energy Agency. It covers the years 1970 to 2004 (IEA 2006).[5] This dataset was supplemented by process emissions from cement production from Marland et al. (2003) to cover all industrial CO_2 emissions
3. Emissions from CH_4 and N_2O as estimated by the US Environmental Protection Agency. It covers the years 1990 to 2005 (USEPA 2006)

[5]IEA calculation is less detailed than national calculations and may be treat distribution losses and feedstock differently.

4. CO_2 emissions from fuel combustion and cement production as published by Marland et al. (2003) as retrieved in 2006. It includes emissions from 246 countries (some no longer present today) from earliest 1750 (only OECD countries) or 1950 to 2003.
5. Regional past data: Edgar/Hyde available for all sectors, 17 regions from 1890 to 1990 (Klein Goldewijk and Battjes 1995).
6. Regional future regional emission data: MNP/RIVM IMAGE 2.2 implementation of the SRES scenarios (IMAGE Team 2001), available for all gases and sectors from 1970 to 2100 for 17 regions.

The new database was then completed by applying an algorithm. For each country, gas and the sectors "energy and industry"[6] and "waste and agriculture", the algorithm comprises the following steps:

1. For all data sets, missing years in-between available years within a data set are linearly interpolated and the growth rate is calculated for each year step.
2. The data source is selected, which is highest in hierarchy and for which emission data are available. All available data points are chosen as the basis for absolute emissions.
3. Missing years are filled by applying the growth rates from the highest data set in the hierarchy, for which a growth rate is available.

A new and important element of this analysis is that we calculated uncertainty bounds (upper and lower limit) for the emission estimates. They are calculated based on fixed uncertainty factors that are differentiated per dataset and sector as provided in Table 1. The values are based on simple assumptions, including IPCC inventory guidelines as default and information provided in Prather et al. (2009). The values are also informed by Marland et al. (1999) who compared the CDIAC and EDGAR datasets. The uncertainty is higher for years further in the past. We characterised these uncertainties as describing the confidence interval of $\pm 1\sigma$, i.e. 16th and 84th percentile.

For example, CO_2 emissions from energy and industry are assumed to be 5% uncertain when reported by the country under the UNFCCC (starting in 1990), 10% when the IEA dataset was used that starts in 1970 and 15% when the CDIAC dataset is used, which starts in 1750 for most countries, based on Marland et al. (1999).

Uncertainty aggregation effects are not considered in the analysis (as e.g. in Prather et al. 2009). When summing the uncertainties over sectors and gases for one country, we add all upper and all lower bounds. We however do not aggregate the uncertainty levels from countries to a global level by direct adding, since this would significantly overestimate the uncertainty.

Some past and future emissions are only available on a regional basis and not country-by-country. In these cases we applied regional growth rates to country level emission estimates. This essentially back casts the current territory of a county into the past; territorial changes are not taken into account. Other methods for downscaling regional growth to individual countries within a region are available

[6] Includes all emissions from energy use (e.g. power production, industrial heat, domestic heating, transport) as well as industrial process emissions (e.g. from cement).

(Van Vuuren et al. 2007). These differentiate the growth within the region based on country specific population and GDP growth. The use of these methods would have an effect on individual countries' past CH_4 an N_2O emissions (not CO_2, as they come from country specific datasets) and on future emissions of all gases. However, when aggregated to regions, the differences between these methods are smaller, because they then add again close to the original regional value used to start with.

For "land use change and forestry", we used a different approach (de Campos 2007). The use of growth rates is not possible here as the estimates can be negative (removals). Hence we used the simple approach of taking two datasets that for the global total represent the two extremes: Houghton (2003) (high) and IVIG, de Campos and Muylaert Rosa (2005) (low). Both datasets were extended to 2100 using SRES scenarios. To downscale from SRES regions to nations, a concept of "potential LUC sink" is used, simply assuming that the more a country has emitted from LUC in the past, the more potential it has to create a sink by reverting to the original biomes. As potential LUC depends on past emissions, this also prolongs the difference between Houghton and IVIG. For further detail on the method see de Campos and Muylaert Rosa (2005). A more sophisticated model should take into account climate feedbacks and changing demand for agriculture etc., this is just a first approximation for reasonable downscaling. For each country the "best estimate" is the average between the two datasets, the upper limit is the maximum of both, the lower limit the minimum.

The resulting estimates and uncertainty are a very rough representation of the historical emissions from land use change and forestry and should be considered with care. Due to different definitions they can be different compared to the values reported by countries under the UNFCCC. For more elaboration on historical emission estimates from LUCF see Ito et al. (2008), a separate join paper by the MATCH group.

Resulting global emissions (best estimate, IPCC 1995 GWP_{100} weighted) provided in Fig. 1. Due to data availability, emissions of CH_4 and N_2O are starting only in 1890. Emissions of CH_4 and N_2O from 1750 to 1890 (assuming a linear increase from zero

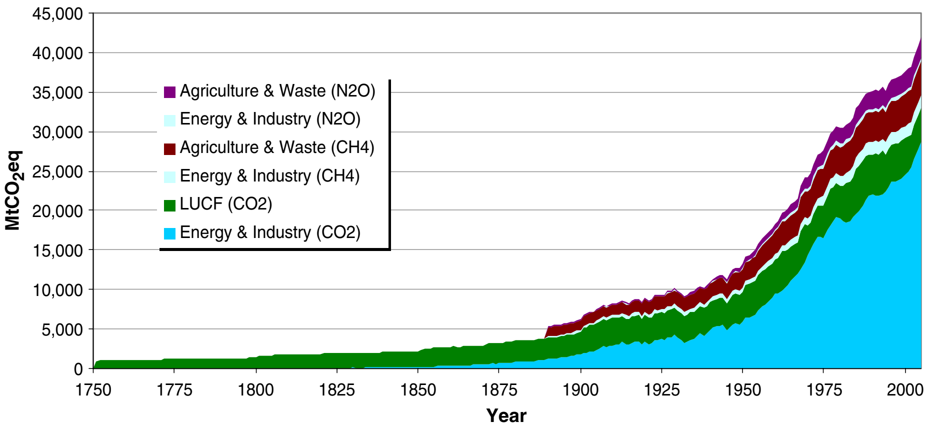


Fig. 1 Best-estimate historical GWP_{100} weighted global emissions per sector and gas

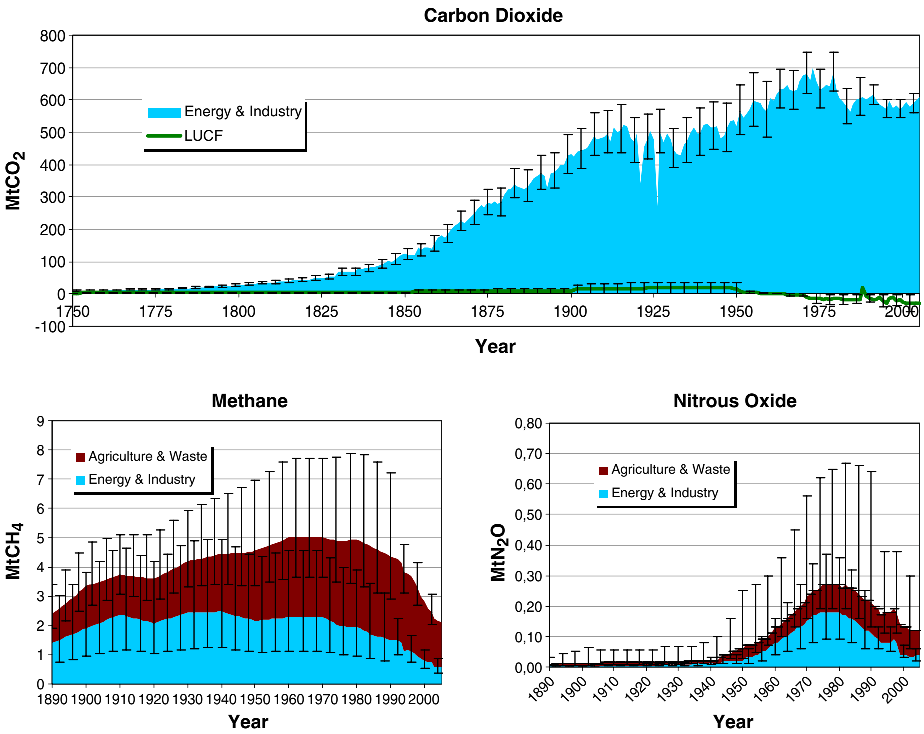


Fig. 2 Historical CO_2, CH_4 and N_2O emissions per sector and associated uncertainty for UK

in 1750 to the value of 1890) would have an impact on temperature change in 2005 smaller than 1%.

Time history and uncertainty of the gases and sectors for UK and Brazil as examples are provided in Figs. 2 and 3. *Relative* uncertainty is larger for past emissions compared to present, but since past emissions are usually smaller than current emissions, the *absolute* uncertainty is not always larger for past emissions.

We observe that the historical emission profiles and associated uncertainties are very different between the example countries UK and Brazil. UK's major part of emissions originates from energy and industry being on a similar level for the past 100 years. LUCF plays a minor role, CH_4 and N_2O have declined in the past 20 years. For Brazil, emissions from LUCF are of major importance, but highly uncertain. CH_4 and N_2O emissions from Agriculture are also significant but also highly uncertain. Emissions from energy and industry are relatively small, but increasing fast in the last 50 years. Both countries have a significantly different profile compared to the world average (Fig. 1) and are therefore sensitive to choices that are made in the calculation of contributions to climate change.

2.2 Experimental setup

All modelling groups calculated results for a number of cases to enable a detailed inter-comparison (Table 2). In the selection of the parameters we chose those that are

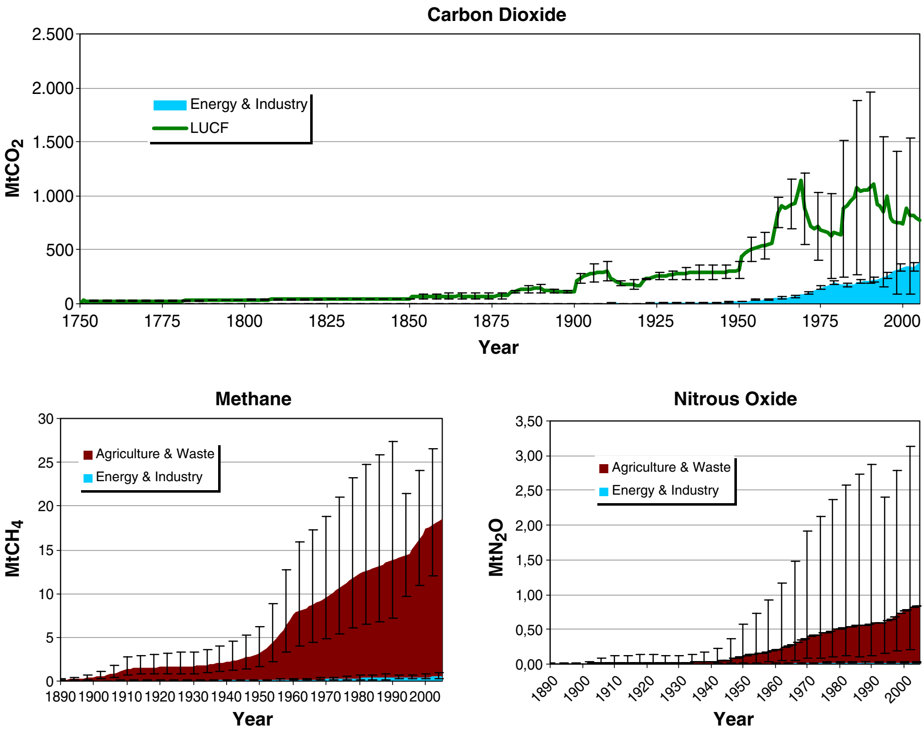


Fig. 3 Historical CO_2, CH_4 and N_2O emissions per sector and associated uncertainty for Brazil

most critical for the results based on detailed discussions in den Elzen et al. (2005a). For each indicator we calculated the absolute contributions (e.g. the effect on global average temperature increase) and the contributions relative to the total from all attributed emissions.

The work concentrates on two indicators, "global warming potential weighted cumulative emissions" and the "effect on global average temperature increase" in the last year of accounted emissions (end date), as these are the two most commonly used indicators. We selected a range of start dates: 1750 where emission datasets start, 1900 as a 100-year time horizon, 1950 as the restart after the Second World War and 1990 when climate change was an internationally recognized phenomenon. In addition to stopping emissions in 2005, we also evaluated contributions for future years using business as usual scenario based emissions based on IPCC SRES scenarios (end dates 2005, 2020, 2050 and 2100). Contributions were calculated per gas and per sector. In addition, due to the more uncertain nature of emissions from LUCF we include a case here these emissions are excluded.

Results are provided as absolute levels and also in relative terms. For the relative value, the contribution of the countries' emissions (high, low or best estimate) is divided by the contribution of the sum over the attributed best emission values for all countries. This is in line with not aggregating the uncertainty levels from countries to a global level by direct adding. Estimates of single gases and sectors are also

Table 2 Alternative experimental settings used by the modelling groups

Contribution	Relative
	Absolute
Indicators	Cumulative GWP weighted emissions (fixed IPCC 1995 GWPs, calculated only by one group)
	Temperature increase at end date
	Temperature increase at 2100
Start dates	1750
	1900
	1950
	1990
End date	2005
	2020
	2050
	2100
Sectors and gases	All sectors and three gases excluding LUCF
	All sectors and three gases including LUCF
	CO_2 only
	CH_4 only
	N_2O only
Emissions	Lower bound
	Best estimate
	Upper bound
Sources (192 + 3)	All separate individual countries (192)
	Globally aggregated sectors: energy + industry, agriculture + waste, LUCF (3)

divided by estimates of the sum of all attributed gases and sectors and no other forcings.

2.3 Climate models

For the calculation of the regional contribution to global climate indicators, i.e. concentrations, radiative forcing, temperature change, different chemistry and climate models are used. These are briefly described below and summarised in Table 3.

Default model As in earlier modelling exercises (den Elzen et al. 2005a), most groups used a simple default model. It is based on Impulse Response Functions (IRFs) for the calculations of concentrations, temperature change and sea level rise, and based on functional dependencies from the IPCC-TAR (Ramaswamy et al. 2001) for the radiative forcing (e.g., logarithmic function for CO_2). For the CO_2 concentration, the IRF is based on the parameterisations of the Bern carbon cycle model of Joos et al. (1996, 1999), as applied in the IPCC-TAR (Third Assessment Report). For the concentrations of the non-CO_2 GHGs, single-fixed lifetimes are used. The total radiative forcing considered here consists of the radiative forcing from CO_2, CH_4 and N_2O plus direct and indirect radiative forcing from aerosols derived by the coupled ocean–atmosphere General Circulation Model (GCM) HADCM3 (Stott et al. 2000). Surface temperature change is modelled using two-term IRFs also derived from the HADCM3 model. The contributions of individual emissions to concentrations, temperature change and sea level rise are calculated by separately applying all

Table 3 Specifications of the models used

Model	Carbon cycle (CO_2)	Atmospheric chemistry (non-CO_2)	Sulphate aerosols	Radiative forcing	Temperature increase	Attribution method
ECOFYS	IRF (Bern)	Fixed lifetimes	–	IPCC-TAR	IRFs (Hadley)	Normalised marginal
IAE-GRAPE	IRF (Bern)	Fixed lifetimes	Hadley data	IPCC-TAR	IRFs (Hadley)	Normalised marginal
BCC_SCM	Bern non-linear	Fixed lifetimes	Hadley and Joos et al.	IPCC-TAR	IRFs (Hadley)	Normalised marginal
CICERO-SCM	Non-linear	IPCC-TAR	IPCC-TAR	IPCC-TAR	EBC/UDO model	Normalised marginal
UKMO	IRF (Bern)	Fixed lifetimes	IPCC-TAR	IPCC-TAR	Upwelling diffusion energy balance model (MAGICC)	Normalised marginal

equations defined at global level to the emissions of the individual emitting regions. The assumption of linearity of these steps in the ACCC model ensures that the sum of the regional contributions is equal to the contribution of the global total. The relationship between concentration and radiative forcing is non-linear ("saturation effect"). Here, the "normalised marginal method" is used as default (taking the effect of small additional emissions normalized so that the sum of all contributions is the total effect, see also den Elzen et al. 2005a).

Three model groups have implemented the default model in different variations: ECOFYS (Höhne and Blok 2005), IAE-GRAPE (Global Relationship Assessment to Protect the Environment) (Kurosawa 2006) and Beijing Climate Center Simple Climate Model (BCC-SCM) (see Table 3). IAE-GRAPE also includes linear interpolation of anthropogenic CH_4 and N_2O data before 1890 for input data adjustment, and assumes sulphate aerosol forcing data from SBSTA climate model comparison (SBSTA, 2002-.FCCC/SBSTA/2002/INF.14)

CICERO simple climate model The CICERO-SCM Fuglestvedt et al. (2001), incorporates a scheme for CO_2 from Joos et al. (1996) and an energy-balance climate/up-welling diffusion ocean model developed by Schlesinger et al. (1992). The SCM calculates global mean concentrations from emissions of 29 gases and radiative forcing for 35 components. The CO_2 module uses an ocean mixed-layer pulse response function that characterises the surface to deep ocean mixing in combination with a separate equation describing the air–sea exchange (Siegenthaler and Joos 1992). It also includes changes in CO_2 uptake by terrestrial vegetation due to CO_2 fertilisation. Parameterisations of tropospheric O_3 and OH as function of NO_x, CO, VOC and CH_4 are taken from IPCC-TAR. Forcings from sulphate aerosols (direct and indirect), fossil fuel black carbon and organic carbon aerosols, biomass burning aerosols, tropospheric and stratospheric O_3 and water vapour are calculated as described in IPCC-TAR and Harvey et al. (1997). The non-linear concentration–forcing relations for CO_2, N_2O and CH_4 (including overlap terms) are from IPCC-TAR.

UK Met office (*UKMO*) used a combination of the ACCC default setting and the MAGICC model. The MAGICC climate model (Model for the Assessment of Greenhouse-gas Induced Climate Change) (Wigley and Raper 2001, 2002) has been used extensively to make climate projections, including being used in the IPCC TAR (Cubasch et al. 2001). The climate model of MAGICC is an upwelling diffusion energy balance model. The atmosphere resolves the land and ocean box in each hemisphere, and there are 40 ocean layers. The model has previously been tuned to credibly emulate the global mean temperature results of seven AOGCMs (Raper and Cubasch 1996; Raper et al. 2001; Wigley and Raper 2002). We estimated perturbations to global mean surface temperature caused by national and sectoral GHG emissions by first calculating the change in the GHG concentrations using IRFs, and then converting this to radiative forcing using TAR formula. A scaled down version of this forcing perturbation was included within a 1750–2100 MAGICC simulation, and the resulting temperature perturbation scaled up at the end of the calculation. In total *x* years of simulations were performed with this model.

A key requirement of the models used is that they can replicate with an acceptable level of accuracy the historical trends in greenhouse concentration and temperature. Table 4 provides the effect of total emissions as used here (best estimate) on

Table 4 Effects of total historical emissions (best estimate) on concentrations, radiative forcing and temperature change according to different models in 2005

	CO_2			CH_4			N_2O			CO_2 + CH_4 + N_2O	CO_2 + CH_4 + N_2O	Climate sensitivity (°C)
	Concentration (ppm)	Radiative forcing (W/m^2)	Temp. increase (°C)	Concentration (ppm)	Radiative forcing (W/m^2)	Temp. increase (°C)	Concentration (ppm)	Radiative forcing (W/m^2)	Temp. increase (°C)	Radiative forcing (W/m^2)	Temp. increase (°C)	
Ecofys	380	1.68	1.03	1.85	0.42	0.27	0.31	0.13	0.07	2.23	1.37	3.68
IAE	375	1.6	n.a.	1.8	0.5	n.a.	0.32	0.17	n.a.	2.27	0.8[a]	n.a.
BCC	385	1.74	1.17	1.64	0.44	0.33	0.32	0.15	0.09	2.33	1.59	3.32
CICERO	386	1.76	n.a.	1.67	0.45	n.a.	0.32	0.17	n.a.	2.38	1.35	2.97
UKMO	376	1.61	0.89	1.71	0.47	0.27	0.34	0.22	0.11	2.29	1.27	3.24

n.a. not available, as it is not a separately calculated variable

[a]Includes also other forcings than CO_2, CH_4 and N_2O

concentrations, radiative forcing and temperature change according to the different models employed. E.g. the second row provides the resulting CO_2 concentration in 2005 based on the total historical CO_2 emissions used in this exercise. It ranges from 375 to 386 ppmv in 2005 compared to measured 378 ppmv.[7] The values for temperature increase are from 1.27°C to 1.37°C well above the observed value of 0.7°C. This is because it includes only the forcing of CO_2, CH_4 and N_2O and does not include the other forcings (except for one model), which to a large part have a cooling effect. Implications on attribution calculations are discussed in den Elzen et al. (2005a).

All models calculated the marginal change in temperature of an emission time series of an individual country, sector and gas combination by subtracting it from global total emissions (best estimate) and comparing the resulting temperature increase with that from global total emissions. Also for the cases where the upper and lower bound of the emission estimate was used for the country, sector and gas combination, the best estimate was used for global total emissions.

The uncertainties in the LUCF CO_2 emissions may lead to different assumptions on carbon cycle feedbacks to calibrate to current concentrations. They therefore also influence the CO_2 concentrations in the future (see Rotmans and den Elzen 1992; den Elzen et al. 1997; Wigley 1993; Friedlingstein et al. 2006). This has not been considered in the models of this paper, they are only calibrated once. Such balancing would have a small effect on the *relative* contributions as the changes would mainly apply to all countries equally, but could change the weight between early and late emissions.

3 Results and analysis

In the following sections we will present a selection of the results. Interested readers may also refer to the electronic results to extract those of interest.[8]

We always show the results for the G8+5 countries (Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russian Federation, South Africa, UK and USA). We also show the results for roughly 10 countries, for which the considered parameter change has the greatest influence. From this analysis we exclude countries that have emissions smaller than 0.1% of cumulative GWP weighted global emissions 1900 to 2005. This threshold applies to 100 countries restricting our analysis to the remaining 92 countries.

A country's result will be changed substantially for different experimental parameters settings if one of the following conditions applies: The split of the country's emissions across gases and sectors is very different to the average (e.g. methane dominated as Brazil, see Fig. 3). Or the timing of the emissions is very different from the world average (e.g. UK having started very early with industrialization, see Fig. 2). For countries that are close to the world average, the change in parameters will not have a significant effect.

[7] http://www.esrl.noaa.gov/gmd/ccgg/trends

[8] Available at http://www.match-info.net

As default we show temperature increase in 2005 from emissions from 1900 to 2005 of all gases and sectors, but explore other parameter settings in the following sections.

3.1 Model uncertainty and emission uncertainty

In a first case we assess the differences in the results between the different models listed in Section 2.3 and compare this spread to the uncertainty that is introduced by unknown historical emission estimates. Figure 4 shows the relative contributions of selected countries to cumulative GWP weighted emissions (model independent) and to temperature increase from different models.

One can observe that the uncertainty introduced into the relative attribution results by the use of different models (difference between the bars 2 to 6 in the figure) is considerably less than that resulting from the uncertainty in historical emissions (error bars). This is partly to be expected since the models are quite similar in structure and are typically tuned to the same historic temperature record. However, the models are not identical. For example, CICERO-SCM is giving a higher weight to methane due the use of a changing lifetime and therefore calculated a higher contribution for, e.g., India, which has a relatively high share of methane emissions.

Earlier work of the MATCH group found very similar results that the model uncertainty is relatively low for *relative* contributions (den Elzen et al. 2005a; Shine et al. 2005; Prather et al. 2009).

Hence, we show in the following sections only results from *one* representative model with the effect of *emission uncertainty* as error bars.

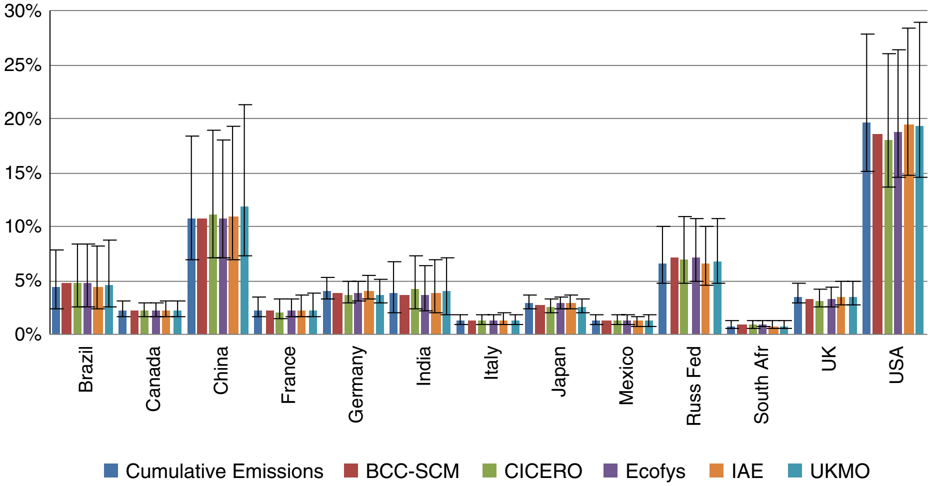


Fig. 4 Relative contribution to cumulative emissions (*first bar*) and to temperature increase in 2005 by different models (*bars 2* to *6*) from emissions from 1900 to 2005 of CO_2, CH_4 and N_2O including LUCF for selected countries. Error bars show the uncertainty only due to historical emission estimates. (BCC did not calculate uncertainty)

3.2 Indicators

In a second case we show the difference in results due to the choice of indicator for historical contributions. Figure 5 shows relative contribution to cumulative emissions (first bar per country), to temperature increase in 2005 (second bar) and to temperature increase in 2100 (third bar) from emissions from 1900 to 2005 of all gases including LUCF as calculated by Ecofys. For the third indicator we assume that perturbation stops after 2005 and the climate system relaxes again until 2100 and compare the effects of countries emissions from 1900 to 2005 in 2100.

In most cases the difference between cumulative emissions and contribution to temperature increase is small, as we found in earlier studies (den Elzen et al. 2005a). It is largest for countries that have a time path of emissions different to the world average. E.g. emissions in Russia were high in the 1980s and are much lower today. Since the high emissions of the 1980s have a full effect on temperature increase and the recent emissions yet have to develop their full effect, The relative contribution of Russia to temperature increase is larger than to cumulative emissions.

The difference between the contributions to temperature increase in 2005 to temperature increase in 2100 is most apparent for countries with a large share of the shorter lived gas methane (e.g. India and Bangladesh). Recent methane emissions have a relatively high impact on today's temperature, but by 2100 this impact has decayed due to the short lifetime of methane.

Figure 6 shows the sensitivity to choosing different indicators for the 92 countries that have emissions larger than 0.1% of cumulative GWP weighted global emissions 1900 to 2005. The figure shows per country the maximum of the relative contribution divided by the minimum for the three choices cumulative emissions, temperature increase in 2005 and temperature increase in 2100 in decreasing order. For example India's contribution is 1.4 times higher using cumulative GWP weighted emissions compared to temperature increase in 2100. This is due to the relatively high share of methane emissions from India, which have a very small effect on temperature in 2100, due to methane's short lifetime. They have a larger effect when using GWPs, because then emissions at all times have the same contribution, earlier emissions are

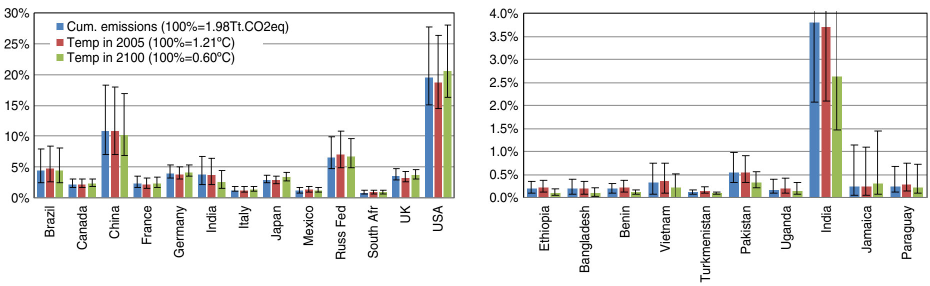


Fig. 5 Relative contribution to cumulative emissions (*first bar*), to temperature increase in 2005 (*second bar*) and to temperature increase in 2100 (*third bar*) from emissions from 1900 to 2005 of all gases including LUCF for countries G8+5 (*left*) and where it makes the most difference (*right*). Error bars show the uncertainty only due to historical emission estimates. Note the different scales on the two figures (Source: ECOFYS)

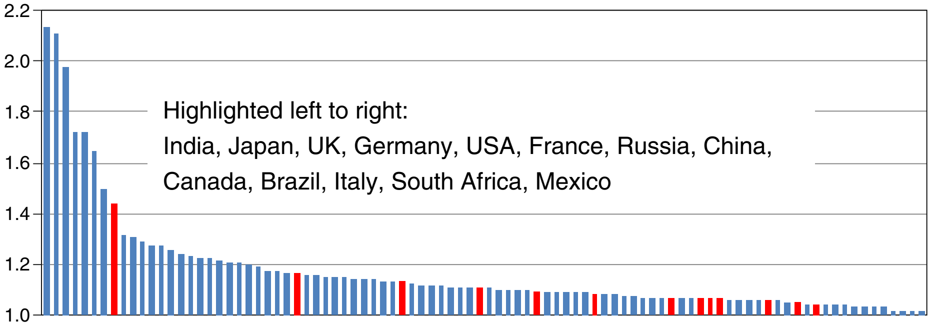


Fig. 6 Sensitivity to choosing the indicator. Maximum divided by the minimum of the relative contribution for cumulative emissions, temperature increase in 2005 and temperature increase in 2100 for the 92 largest countries. G8+5 countries are highlighted (Source: ECOFYS)

not "physically discounted" by the climate system (Fuglestvedt et al. 2009; Shine et al. 2005).

We see that for some countries, the difference might be high (up to factor of 2), while for most countries the difference is around 10% (i.e. around 1.1 in the Fig. 6).

3.3 Start dates

As a third case we show the influence of choosing a different year as of which to start accounting for emissions. Figure 7 shows the relative contribution to temperature increase in 2005 due to emissions from 1750, 1900, 1950 and 1990 to 2005 of all gases including LUCF.

The difference is large for countries with emission profile well different to the global average: rapid increase in emissions recently (e.g. United Arab Emirates or South Korea) or currently decreasing emissions (e.g. UK).

The uncertainty introduced by unknown historical emissions increases when moving to earlier emissions. Emissions in the 1990s are relatively well known, uncertainty is relatively small, but moving to 1900 the uncertainty increases for some

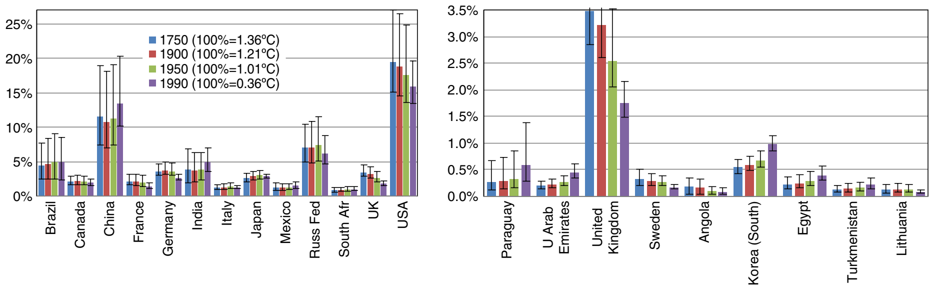


Fig. 7 Relative contribution to temperature increase in 2005 from emissions from 1750, 1900, 1950 an 1990 to 2005 of all gases including LUCF for G8+5 countries (*left*) and where it makes the most difference (*right*). Error bars show the uncertainty only due to historical emission estimates (Source: ECOFYS)

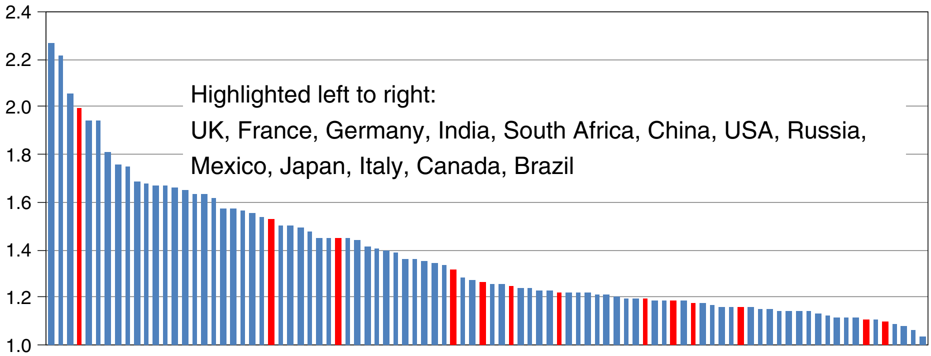


Fig. 8 Sensitivity to choosing the start date. Maximum divided by the minimum of the relative contribution for start dates 1750 to 1990 for the 92 largest countries. G8+5 countries are highlighted (Source: ECOFYS)

countries. It does not significantly increase when moving further to 1750 because the additional emissions are usually very small compared to recent emissions, although very uncertain.

Figure 8 provides the sensitivity to choosing different start dates for the 92 countries that have emissions larger than 0.1% of cumulative GWP weighted global emissions 1900 to 2005. The figure shows per country the maximum of the relative contribution divided by the minimum for start dates 1750, 1900, 1950 and 1990 in decreasing order.

We see from the figure that the change in start date is significant for most countries. Within the G8 it is most significant for UK, France and Germany with a long emission history.

3.4 LUCF, non-CO_2 gases

As a fourth case we study the influence of including or excluding emissions from land-use change and forestry as well as the non-CO_2 gases CH_4 and N_2O. These emissions are significant for some countries but the emissions are also more uncertain compared to CO_2 from energy and industry. Figure 9 shows the relative contribution to temperature increase in 2005 from emissions from 1900 to 2005 of all gases including and excluding LUCF, for CO_2 only (including LUCF) and for CO_2 from energy and industry only.

The difference is large for countries with high emissions from deforestation and/or from CH_4 and N_2O. For the G8+5 countries this applies in particular to Brazil, China and India. Annex I countries usually have lower relative contributions when all gases and sectors are considered (most apparent for Japan). Most sensitive countries are those with low state of development (low CO_2 emissions from energy and industry) but large emissions from agriculture and deforestation.

Uncertainty in the relative contribution due to unknown historical emissions (error bars in Fig. 9) is smaller for the case of CO_2 from energy and industry only (since for this case emissions are relatively well known) and much larger when other gases and sectors are included.

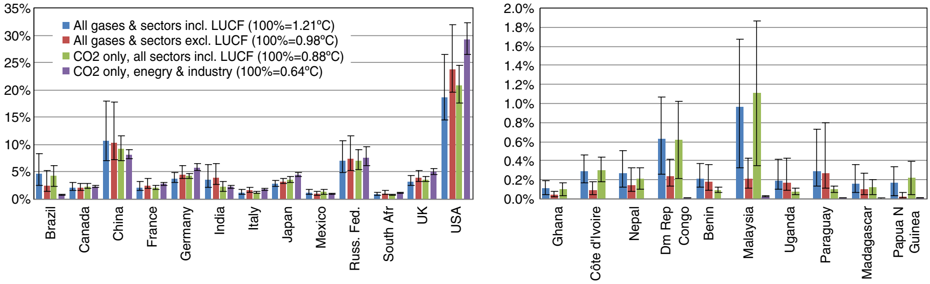


Fig. 9 Relative contribution to temperature increase in 2005 from emissions from 1900 to 2005 of all gases including and excluding LUCF and non CO_2 gases for G8+5 countries (*left*) and where it makes the most difference (*right*). *Error bars* show the uncertainty only due to historical emission estimates (Source: ECOFYS)

Figure 10 provides the sensitivity to including/excluding LUCF and non-CO_2 gases for the 92 countries that have emissions larger than 0.1% of cumulative GWP weighted global emissions 1900 to 2005. The figure shows per country the maximum of the relative contribution divided by the minimum for the four cases in Fig. 9 in decreasing order.

We see that for quite a few countries, e.g. Indonesia, the inclusion or exclusions matters substantially up to a factor of 10 to 90. For the G8+5 countries it is most significant for Brazil and India (a factor of 5 and 2, respectively).

3.5 Split of sectors and gases

We also show the contribution of the different sectors and gases. Figure 11 shows the relative contribution to temperature increase in 2005 from emissions from 1900 to 2005 of all sectors and gases split by sector or by gas.

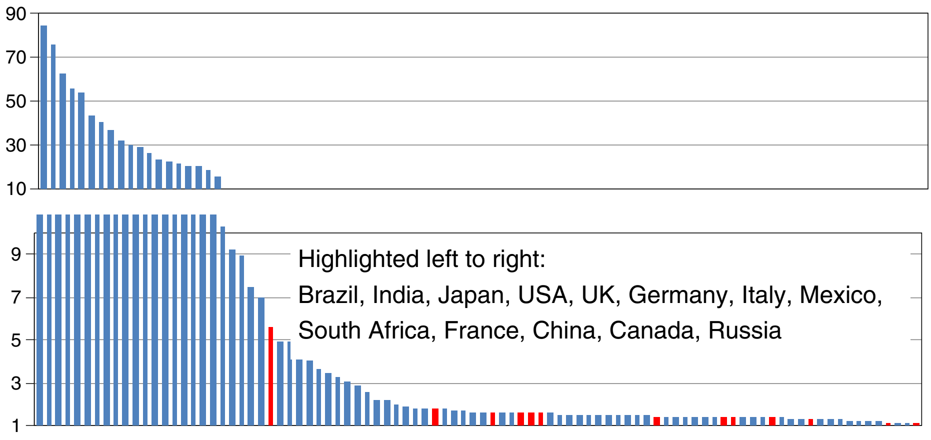


Fig. 10 Sensitivity to including/excluding LUCF and non-CO_2 gases. Maximum divided by the minimum of the relative contribution for the four cases in Fig. 9 for the 92 largest countries. G8+5 countries are highlighted (Source: ECOFYS)

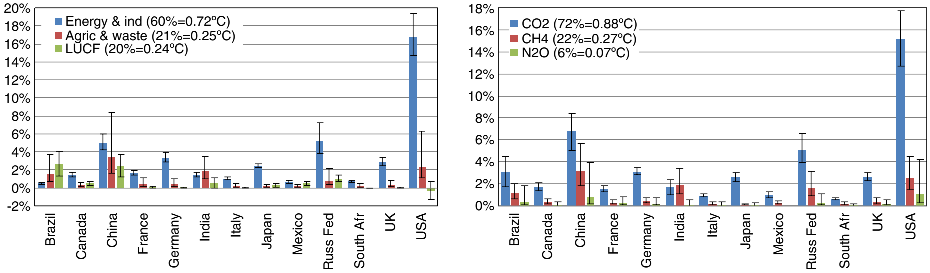


Fig. 11 Relative contribution to temperature increase in 2005 from emissions from 1900 to 2005 split by sectors (*left*) and gases (*right*) for G8+5 countries. In both cases 100% = 1.21°C. Error bars show the uncertainty only due to historical emission estimates (Source: ECOFYS)

For most countries emissions from energy use and industry are contributing most, except for Brazil, where CO_2 emissions from LUCF and agriculture and waste have a higher contribution (Fig. 11, left). CO_2 is the dominant gas for most countries, except India, where the contribution of methane to current temperature is higher (Fig. 11, right). (See Skeie et al. 2009 for calculations of contributions to global warming from the transport sectors).

3.6 Future emissions

The contribution to temperature change in the future caused by future emissions for each country is calculated using the SRES A1B scenario (IMAGE Team 2001). Figure 12 presents relative contributions from the G8+5 countries to temperature

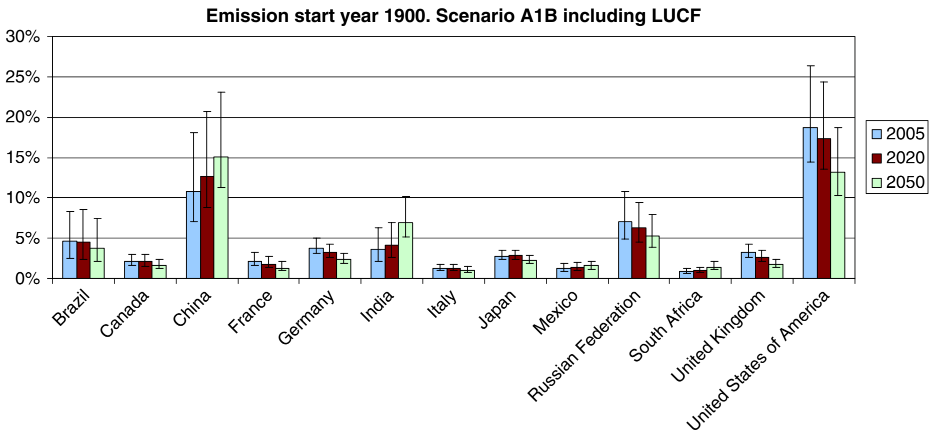


Fig. 12 Relative contribution to temperature change at three different end years (2005, 2020 and 2050). The ECOFYS-ACCC model is used with emission for all gases including LUCF with start date 1900. The future emission scenario used is A1B. The error bars show uncertainty due to emission estimate. Total temperature change 2005: 1.2°C, 2020: 1.6°C and 2050: 2.7°C (sum of countries) (Source: ECOFYS)

change in 2005, 2020 and 2050. The emission start date used is 1900. For Annex I countries like United States of America, Russian Federation, Germany and United Kingdom, the relative contribution to temperature change decreases over time, due to their decreasing share in global emissions. The relative contribution to temperature change from China and India increases over time, due to fast-growing emissions from these two countries. China is currently undergoing a fast emission growth and in the A1B scenario the emissions from China will level out at the end of the period. The rapid emission growth for India is offset by some decades in comparison to China. The results of this can be seen in Fig. 12 where the growth in relative contribution between 2020 and 2050 are larger for India than for China.

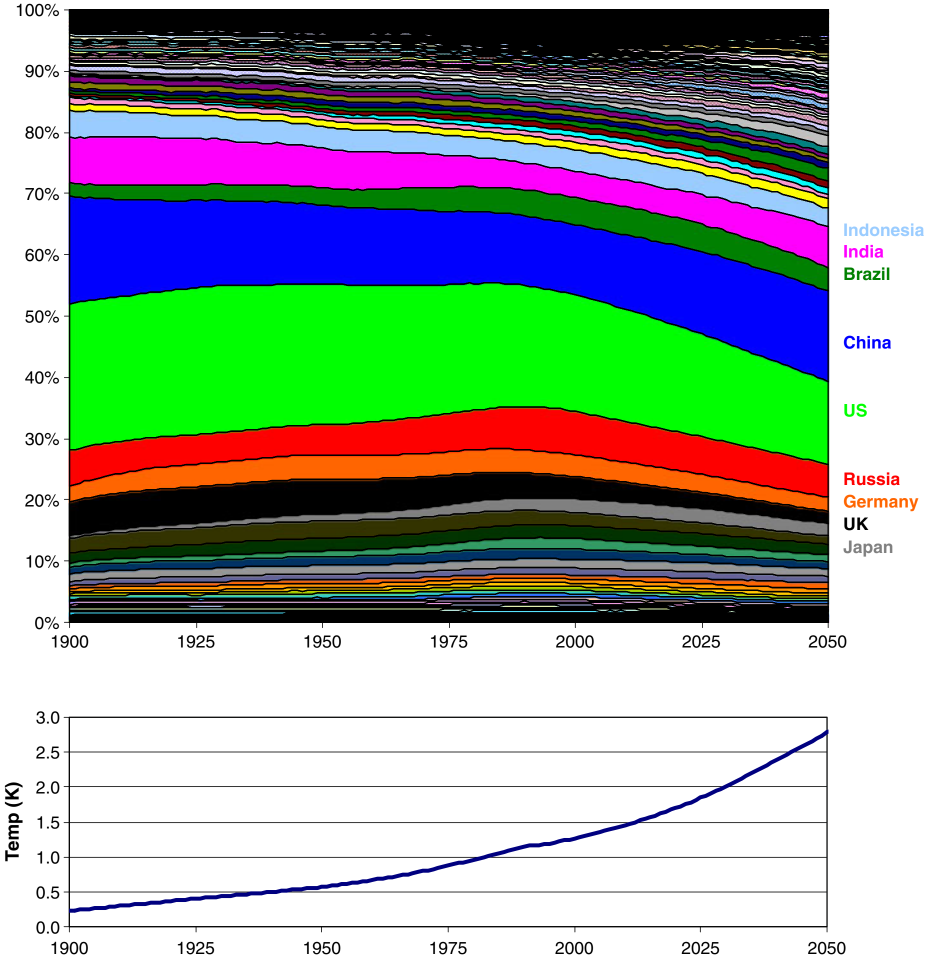
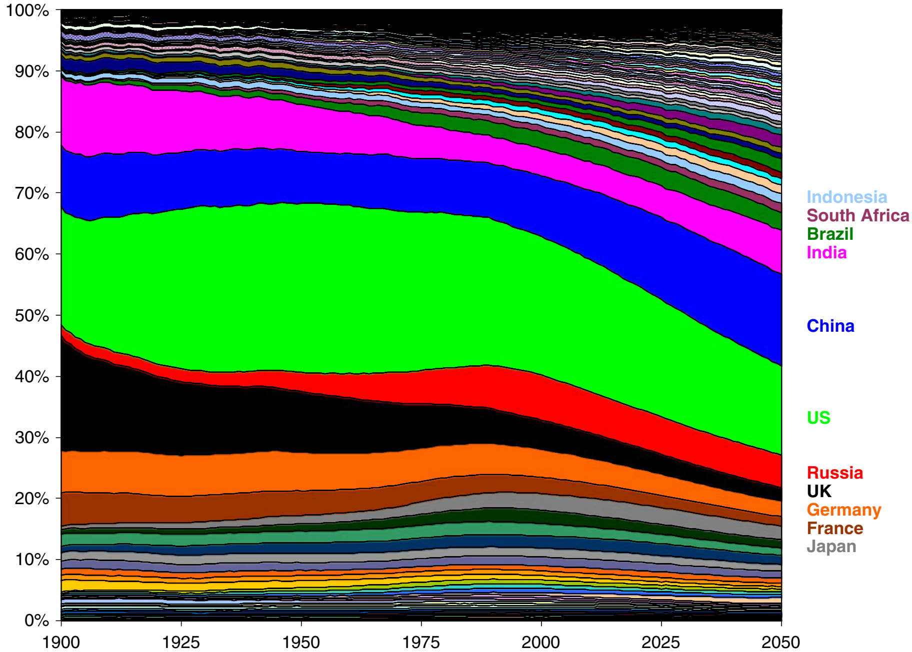


Fig. 13 All countries' relative contribution to temperature change (*top*) from emissions (best estimate) for all gases *including LUCF* from 1750 to the year in the figure. The future emission scenario used is A1B. Industrialized countries' on the bottom, developing countries' on the top, largest contributors are identified by name. Total temperature change is also shown (*bottom*) (Source: CICERO)

The calculations are also done for comparison with the SRES B2 scenario emissions (IMAGE Team 2001). The same pattern is seen in the results for B2 as in Fig. 12 for the A1B scenario, although the size of the contributions in 2050 are somewhat different. In 2050 there are higher relative contribution when using B2 scenario instead of A1B scenario for United States of America, United Kingdom, China, Brazil, France, Germany, Italy, Japan and Canada. For India, Russia, South Africa, Mexico the relative contribution are lower in the B2 scenario compared to the A1B scenario. The differences are usually a few percentage points and within the range of uncertainty given here based on emission uncertainty.

Figure 13 shows relative contribution to climate change as function of time for all countries calculated by the CICERO Simple Climate Model. In the calculations the historical emissions from 1750 for all three gases and all sectors are used and



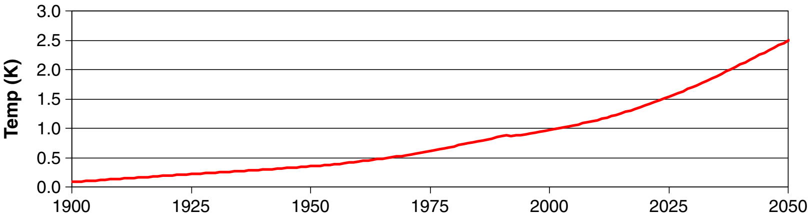


Fig. 14 All countries' relative contribution to temperature change (*top*) from emissions (best estimate) for all gases *excluding LUCF* from 1750 to the year in the figure. The future emission scenario used is A1B. Industrialized countries' on the bottom, developing countries' on the top, largest contributors are identified by name. Total temperature change is also shown (*bottom*) (Source: CICERO)

SRES A1B emission scenario is used for the future up to 2050. In the figure countries are sorted with the non-Annex I countries on the top and the Annex I countries at the bottom. Within these two groups, the countries are sorted by the size of CO_2 emissions in 2005.

Although industrialised countries started much earlier with CO_2 emissions from energy use, developing countries' emissions from land use change and forestry as well as of CH_4 and N_2O are substantial relatively early. Early in the period shown in the figure, there are large relative contributions from non-Annex I countries, although the absolute contribution to temperature change is low (Fig. 13, bottom).

Looking 50 years into the future, the contribution to temperature change from Annex I countries as a group is decreasing, as the emission scenarios assume faster growth of emissions from developing countries.

To see the effect of the relatively uncertain emission estimates form LUCF, we performed the same calculation, but excluding LUCF (Fig. 14). Non-Annex I countries contributions are lower compared to the case including LUCF, especially Brazil, Indonesia and China, while early industrialized countries like Germany and United Kingdom contributions to temperature change are higher. The pattern for the future does not change much, since the LUCF emissions assumed in the future scenarios constitute a small fraction of future total CO_2 emissions.

4 Conclusions

In this paper we compiled historical greenhouse gas emissions and their uncertainties for the first time on country and sector level for all anthropogenic sources of CO_2, CH_4 and N_2O. These emission data were used to calculate national contributions to total cumulative emissions and to global average temperature increase in the past and the future. From this work we draw the following conclusions:

Uncertainty in historical emission estimates differs between countries due to different shares of greenhouse gases and time history. Countries' emissions are more uncertain where the shares of CH_4 and N_2O emissions and of CO_2 emissions from land-use change and forestry are high. The range of emissions from LUCF were estimated in a crude way and would benefit from further refinement, although this is unlikely to change our main conclusions.

The large uncertainty of emissions from the distant past is not dominating the uncertainty of contributions to cumulative emissions and current temperature increase for most countries and most indicators. These indicators are mainly influenced by recent (high) emissions, which are relatively well known. Roughly half of the global total cumulative emissions have happened after 1980. Although emissions from long ago are much more uncertain, their influence on total contributions is relatively small.

A previous MATCH effort (Prather et al. 2009) focussed on the *absolute* contribution to temperature increase and absolute uncertainty of the contributions. They find that uncertainties can be calculated along the full cause effect chain from emissions to temperature increase.

For *relative* contributions, the uncertainty introduced by unknown historical emissions is larger than the uncertainty introduced by the use of different climate and carbon cycle models. To a certain extent this is the case since some of the models are similar. But even when comparing to more sophisticated models this relationship holds (see also Prather et al. 2009).

The choice of different parameters in the calculation of *relative* contributions is most relevant for countries that are different from the world average in greenhouse gas mix and timing of emissions. Historical emissions of countries with high share of the short lived gas CH_4 have a relatively high contribution to temperature increase today but relatively low contribution to temperature increase in 2100. Countries that started emitting early usually have a significantly higher relative contribution, when early emissions are taken into account.

The choice of the indicator has a large effect for the estimates contributions for a few countries (up to a factor of 2) and could be considered small for most countries (in the order of 10%). The choice of the start date is important for many countries, up to factor 2.2 and on average of around factor 1.3. Including or excluding LUCF or non-CO_2 gases changes relative contributions dramatically for a third of the countries (factor 5 to factor 90).

Industrialised countries started to increase CO_2 emissions from energy use much earlier. Developing countries' emissions from land use change and forestry as well as of CH_4 and N_2O were substantial before their emissions from energy use. Looking 50 years into the future, the contribution to temperature change from developed countries as a group is decreasing, as the emission scenarios assume faster growth of emissions from developing countries. Emission estimates from LUCF used in this calculation are rough estimates.

More analysis on estimates from LUCF is needed to understand the large differences in emission estimates from this sector. Ito et al. (2008) made a first start, but additional work is necessary. In addition, it may be useful to investigate a finer sectoral resolution, focussing e.g. on power production or agriculture.

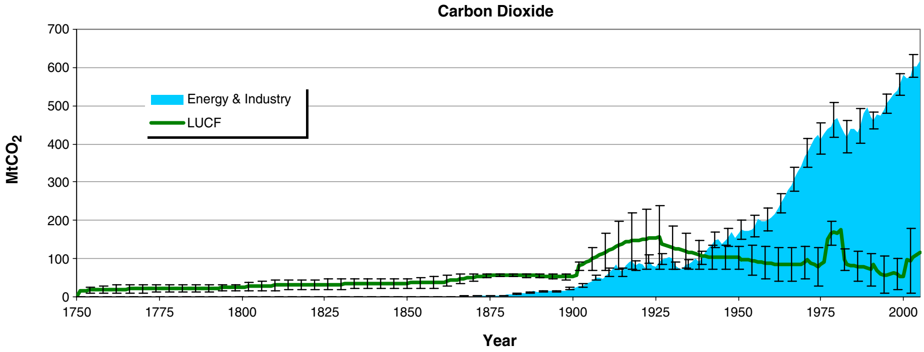
This paper provides for the first time calculations of historical emissions on a country and sector level with uncertainties, cumulative emissions and their effect on global temperature increase and related indicators, considering also varying calculation methodologies. The results are calculated for a wide range of policy related choices. Our new database on emissions and contributions to climate change are available electronically.[9] With these results the international discussion on historical emissions of countries and their related historical contributions to climate change can be put on a stronger quantitative basis.

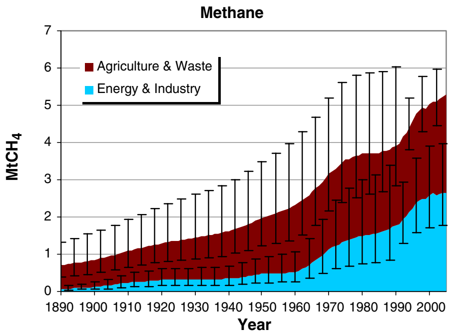
Acknowledgements The authors would like to thank the experts of the ad-hoc group for modelling and assessment of contributions to climate change (MATCH) for their useful comments and suggestions during the MATCH meetings. Developing countries experts travel costs were supported by governments of UK, Germany and Norway. Brazilian researchers benefitted from financial support provided by GARTA/IVIG and MCT (Government of Brazil). We thank the anonymous reviewers of the manuscript for their constructive comments.

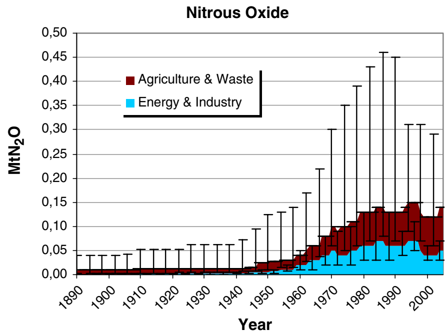
Annex: G8+5 countries historical CO_2, CH_4 and N_2O emissions and uncertainty range

[9] http://www.match-info.net

Canada







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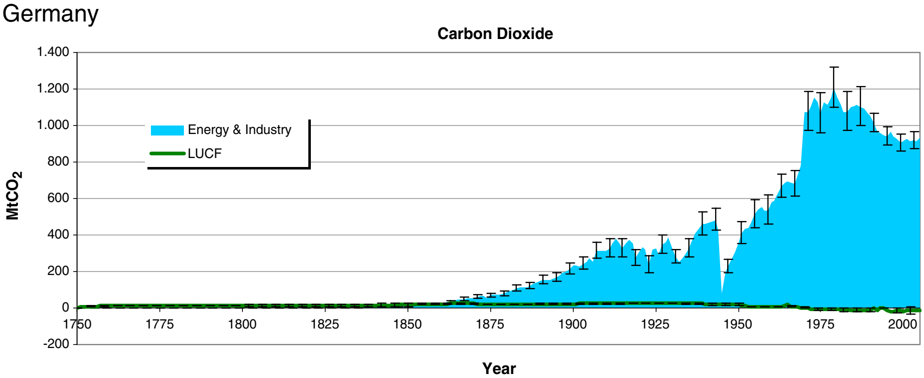

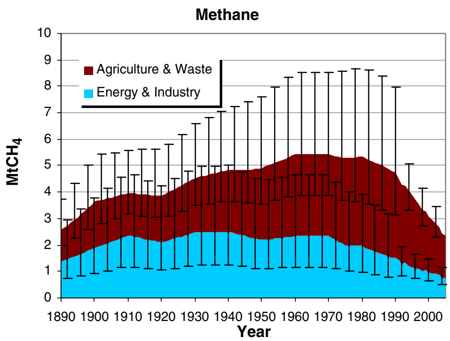

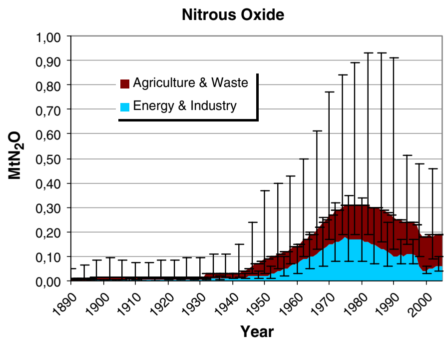

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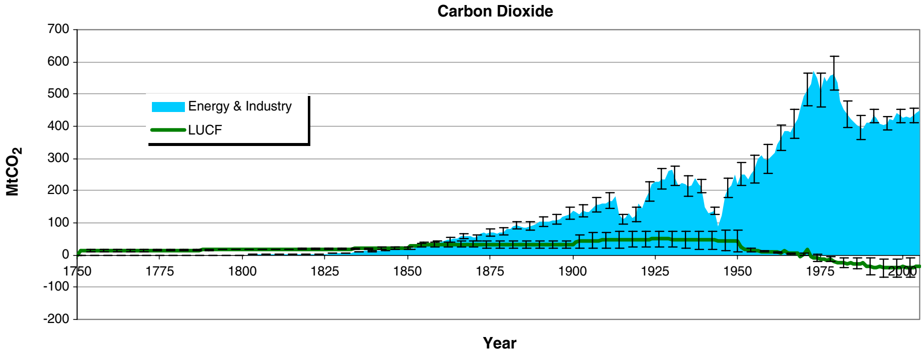

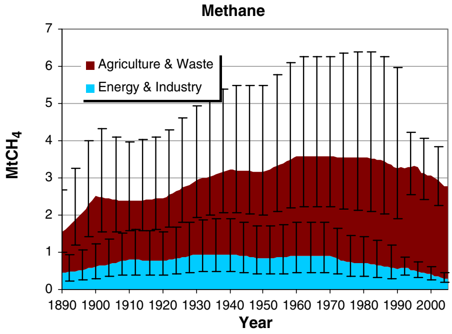

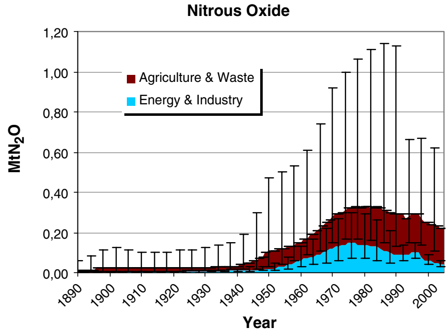

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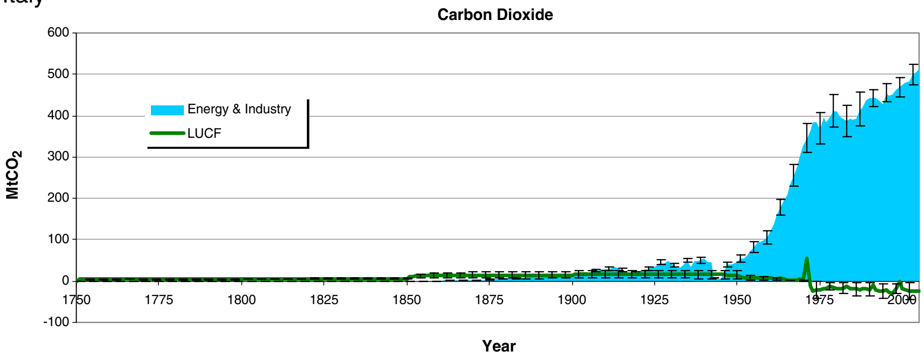

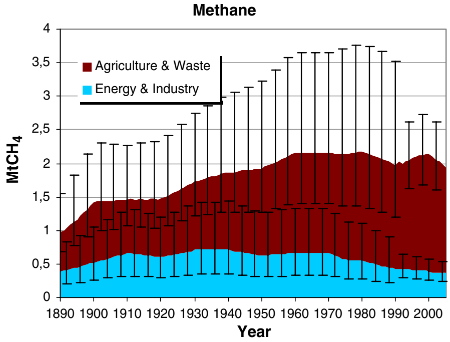

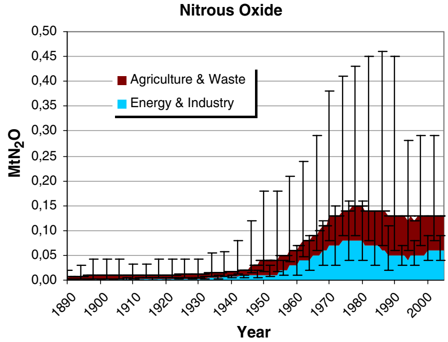

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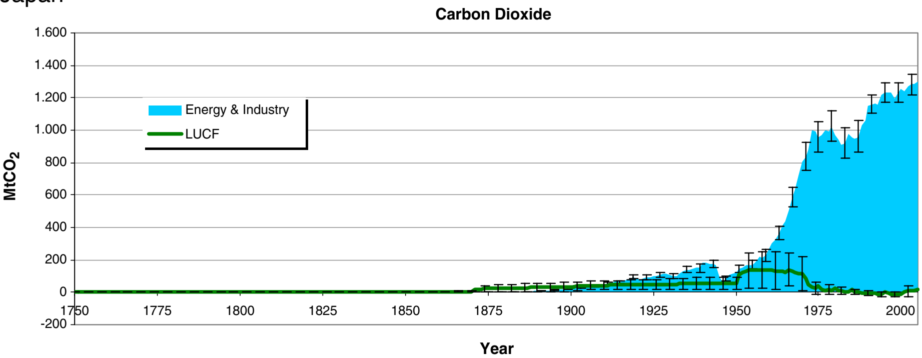

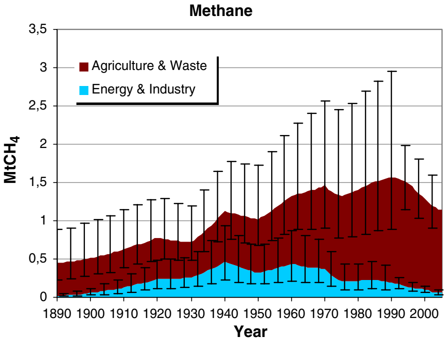

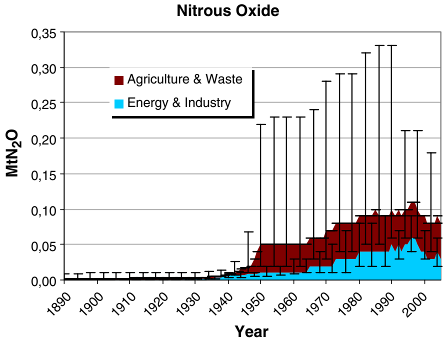

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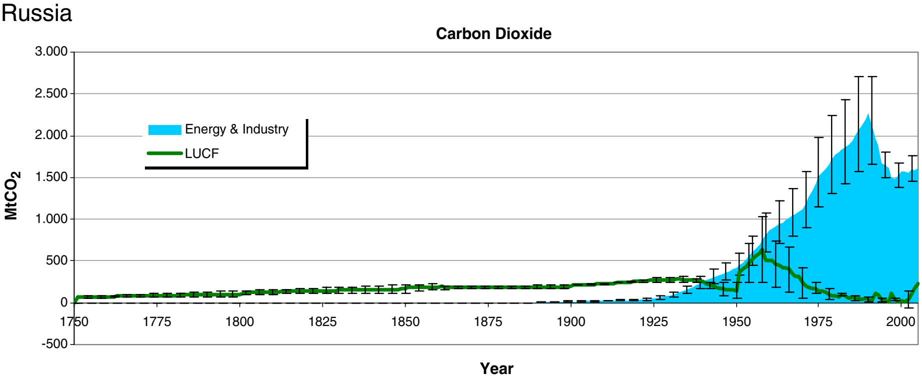
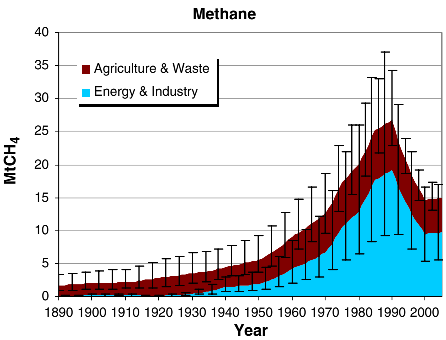
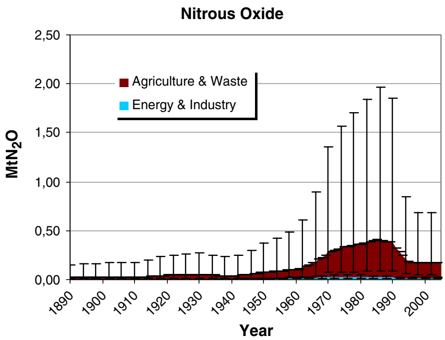
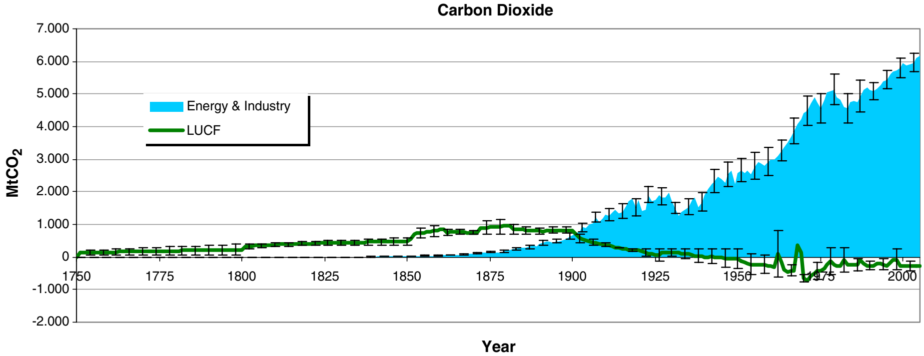
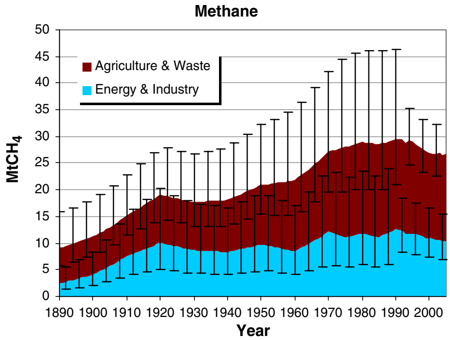


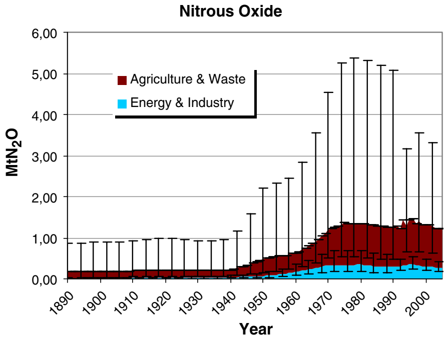




United States of America







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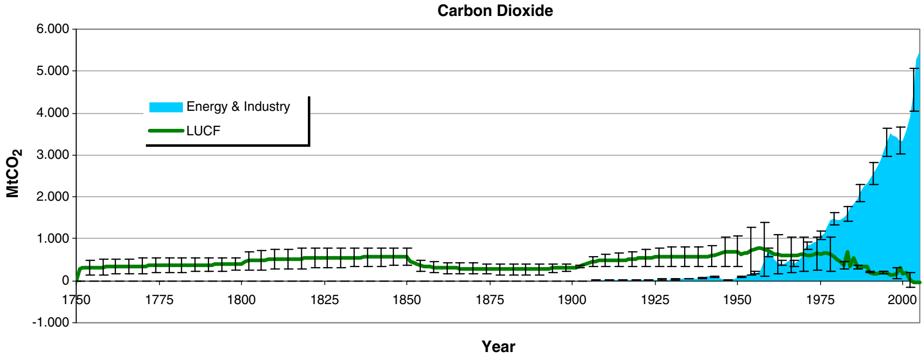

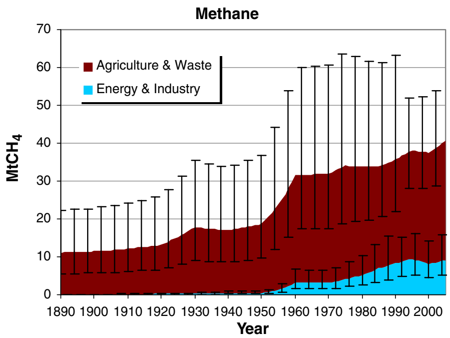

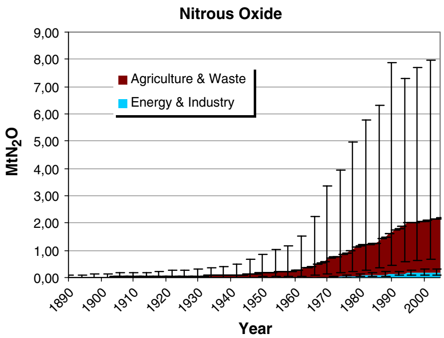

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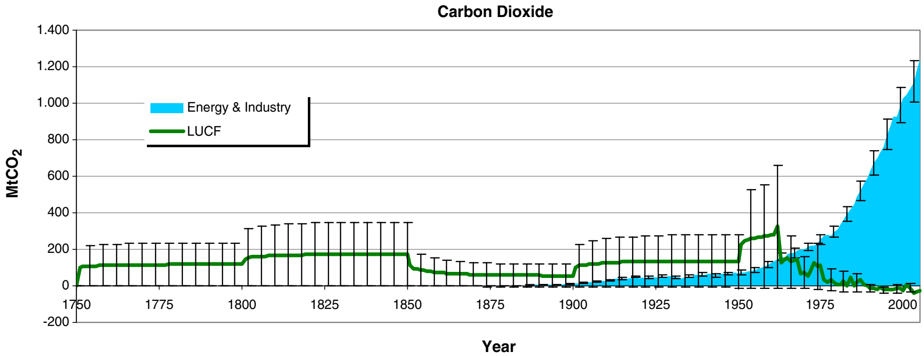

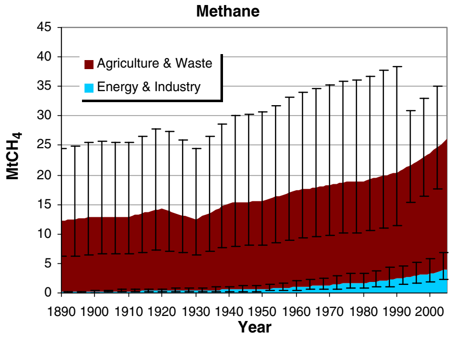

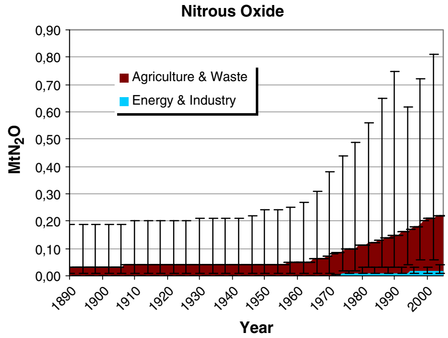

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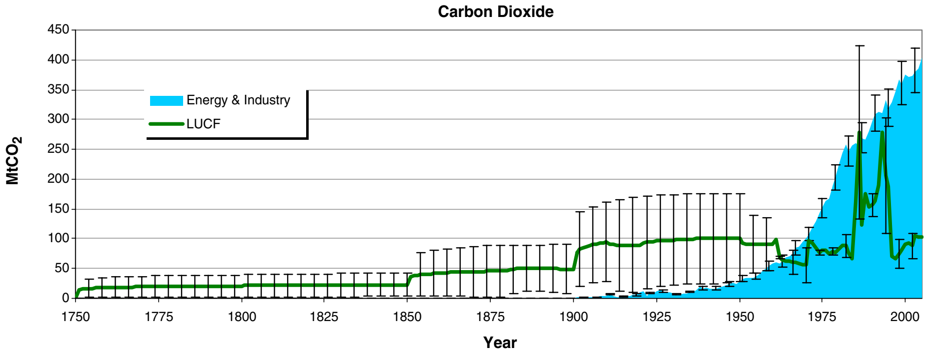

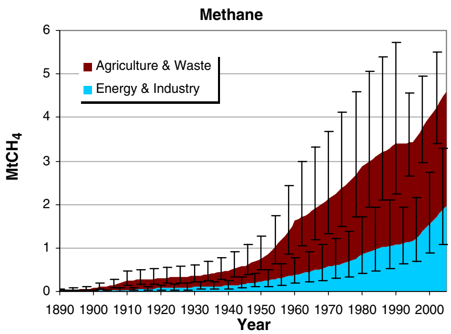

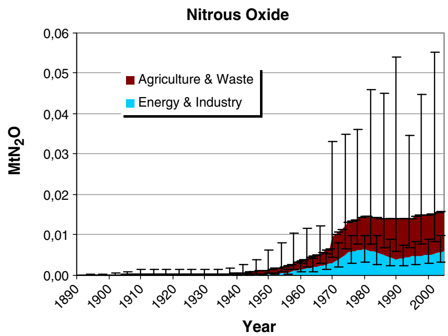

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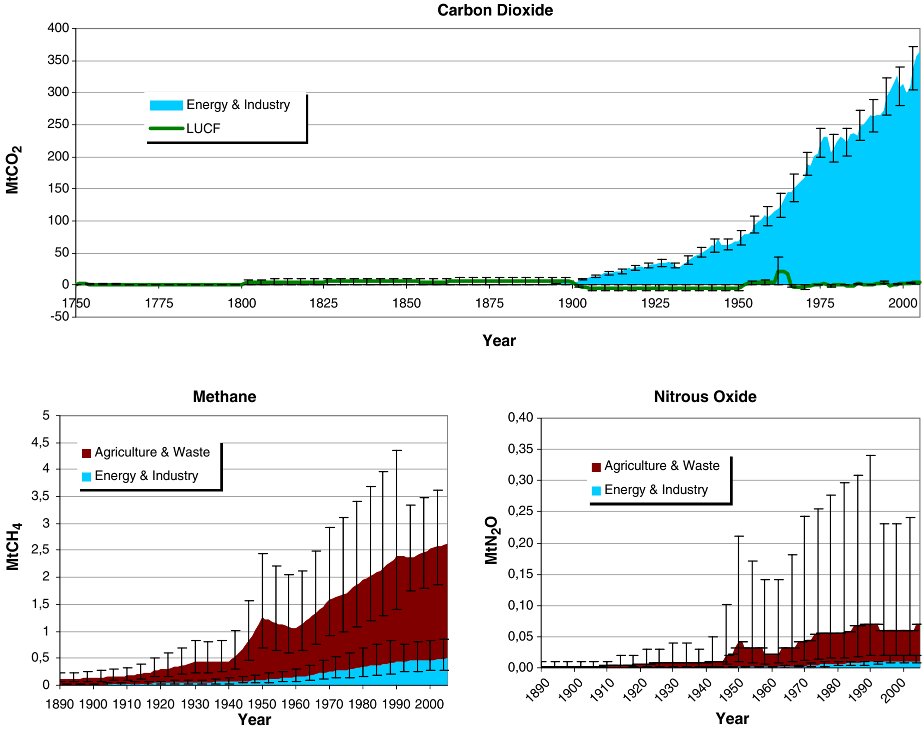

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